Acquisition Directorate

Research & Development Center

Report No. CG-D-09-12

Technical Report on DOMICE Simulation Model

Distribution Statement A: Approved for public release; distribution is unlimited.

April 2012

Homeland Security

N O T I C E

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Technical Report Documentation Page

1. Report No.
CG-D-09-12

2. Government Accession Number

3. Recipient's Catalog No.

4. Title and Subtitle
Technical Report on DOMICE Simulation Model

5. Report Date
April 2012

6. Performing Organization Code
Project No. 7516

7. Author(s)
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8. Performing Report No.
R&DC UDI #1213

9. Performing Organization Name and Address
ABS Consulting, Inc.,
1 Chelsea Street
New London, CT 06320

U.S. Coast Guard
Research and Development Center
1 Chelsea Street
New London, CT 06320

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
HSCG32-08-D-R00007/
T.O. HSCG32-11-J-20085

12. Sponsoring Organization Name and Address
U.S. Department of Homeland Security
Commander (LANT-73)
U.S. Coast Guard Atlantic Area
431 Crawford St.
Portsmouth, VA 23704-5004

13. Type of Report & Period Covered
Final

14. Sponsoring Agency Code
Atlantic Area (LANT-73)
Portsmouth, VA 2704

15. Supplementary Notes
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16. Abstract (MAXIMUM 200 WORDS)
The Domestic Ice Breaking (DOMICE) Simulation Model was developed to update the Operational Risk Assessment Model (ORAM) and add additional rigor to its analysis capabilities related to the United States Coast Guard (USCG) DOMICE mission. Additionally, the DOMICE Simulation Model provides a more complete assessment of risk associated with ice breaking activities by analyzing the various levels of impacts incurred from unmet ice breaking demand.

The DOMICE simulation model allows for a range in possible risk outcomes to be considered based on variables that affect DOMICE operations. The user establishes the initial conditions for each simulated ice breaking season. The DOMICE Simulation Model provides USCG Atlantic Area the ability to assess risk associated with ice breaking asset deployments and variations in operational and natural environments.

17. Key Words
Icebreaking, U.S. Coast Guard, modeling, simulation, service life extension program, WLB, WLM, WTGB, WYTL, WLBB, DOMICE

18. Distribution Statement
Distribution Statement A: Approved for public release; distribution is unlimited.

19. Security Class (This Report)	20. Security Class (This Page)	21. No of Pages	22. Price
UNCLAS//Public	UNCLAS//Public	40	

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EXECUTIVE SUMMARY

The Domestic Ice Breaking (DOMICE) Simulation Model was developed to update the Operational Risk Assessment Model (ORAM) and add additional rigor to its analysis capabilities related to the United States Coast Guard (USCG) DOMICE mission. In the face of an aging domestic icebreaker fleet, there is a growing need to more fully assess the implications of Service Life Extension Programs (SLEP) and unscheduled maintenance in order to mitigate potential consequences of reductions in ice breaking capabilities. There is also a need to examine further the risk associated with a number of varying conditions that significantly affect DOMICE operations, such as varying levels of winter severity and differences in waterway characteristics.

Industrial statistician George Box is generally credited with the quote, "essentially, all models are wrong, but some are useful." With that thought in mind, the DOMICE Simulation Model is a tool for the USCG to quantify the risk associated with different ice breaking asset allocation decisions and varying conditions in both operational and natural environments. Additionally, the DOMICE Simulation Model provides a more complete assessment of risk associated with ice breaking activities by analyzing the various levels of impacts incurred from unmet ice breaking demand. Some consequences of insufficient ice breaking activities considered in the model include the economic impacts felt by operators and consumers related to delayed or displaced cargo shipments, as well as the impacts of damages related to ice-induced flooding incidents. By incorporating both these varying conditions and levels of impacts that have been excluded from prior versions of ORAM, the DOMICE Simulation Model allows ORAM to quantify risk with unprecedented levels of detail in order to improve icebreaker deployment strategies in USCG Districts 1 and 9. The current version of the model uses a one-week time step to coincide with National Ice Center data incorporated into the model. As a result, delays to shipping occur in one-week increments, and the model overestimates the economic impact as delays historically have lasted only a matter of a few days, at most. However, because the model is consistent, the results may be used to evaluate the *relative* change in risk under different assumption sets.

The DOMICE Simulation Model was developed with the objective of incorporating three key factors and sources of variability in a risk analysis of DOMICE operations that were not originally addressed by ORAM. These factors include:

- Winter Severity: The DOMICE Simulation Model was designed to consider winter and ice severity as variable conditions, and to have the ability to simulate the impact of different levels of winter severity;
- Operational Requirements Specific to Individual Waterways: The DOMICE Simulation Model was designed to account for characteristics specific to individual waterways, such as channel depth, width, and probability and degree of icing, that affect icebreakers' operational abilities; and
- Risk Metrics: The DOMICE Simulation Model was developed to use available information on commodity flows and other economic impacts in order to estimate the economic impact of waterway closures. The model utilizes metrics to compare the impacts of the following three main risk drivers: the economic impacts from an inability to ship goods; the consequences of the inability to ship home heating oil to ice-locked communities; and property loss and damage due to ice-induced flooding.

The DOMICE Simulation Model was created in the commercially available off-the-shelf software Analytica. Figure ES-1 provides a conceptual overview of the DOMICE Analytica model and the relationships between the main modules. As the arrows between the nodes imply, the calculated "DOMICE Outcomes" depend on both the "Ice Breaking Demand" and "Ice Breaking Supply" modules. The "Economic Impact" module impacts both the Supply and Demand modules.

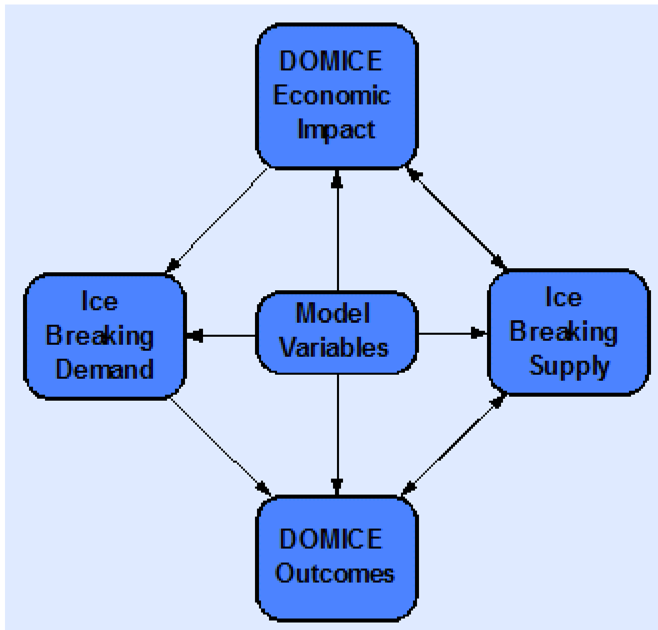

Figure ES- 1. Overview of the DOMICE model.

The DOMICE simulation model allows for a range in possible risk outcomes to be considered based on variables that affect DOMICE operations. The most significant variables that affect the demand for ice breaking activities involve variations in winter severity and vessel traffic flows. Changes in the inventory of ice breaking assets, as well as varying capabilities and availabilities of these assets, are significant sources of variability in the supply of ice breaking resources. These variations, in combination with variations in the extent of the impact incurred by waterway closures, affect the possible range in the total economic risk associated with DOMICE deployment decisions. The model is structured to allow the user to adjust a variety of conditions in order to observe the risk associated with these changing variables. The user establishes the initial conditions for each simulated ice breaking season. The user can manipulate inputs of the "Ice Breaking Demand" module by selecting winters of varying severity. Additionally, the user can adjust the inputs of the "Ice Breaking Supply" module by choosing alternative deployments of ice breaking assets, and by determining the number and type of ice breaking operations required to maintain a waterway open to vessel traffic.

To further capture these variations and potential ranges in risk outcomes, the model processes multiple types of data through probabilistic simulations to accurately account for the probabilities of the occurrence of events. This probabilistic sampling approach is known as Monte Carlo simulation. Specifically, the model runs multiple iterations for one complete run of the model using the user-specified allocation of assets. Each iteration of the model randomly selects data from a given year, and after many Monte Carlo iterations have been run, the final model outputs reflect probabilistically-representative risk profiles associated with that particular inventory of ice breaking assets. For example, if the user selects to run the model based on random years of ice severity data, the model will run the first iteration using weather data from a randomly-selected winter navigation season, followed by a second iteration using another randomly-selected data year, and so on, until the specified number of Monte Carlo iterations have been completed. One simulation run or iteration of the DOMICE model represents one winter navigation season, which is considered to be 20 weeks in duration. The model's sub-processes run on a week-to-week basis in order to capture changing conditions throughout the season.

The DOMICE Simulation Model provides USCG Atlantic Area the ability to assess risk associated with ice breaking asset deployments and variations in operational and natural environments. The model's output of the total economic impact of waterway closures informs USCG decision-making processes involved in ice breaking asset allocations in Districts 1 and 9. The model's adaptability based on user-specified inputs allows the risk analysis to focus on specific risk-related scenarios. For example, the risk associated with the assignment of one 140-foot WTGB to a Service Life Extension Program can be analyzed by removing this asset from the icebreaker fleet in a run of the model. Additional manipulation of model inputs allows the user to observe changes in risk as a function of varying winter conditions that may reduce or increase the impacts of assigning the asset to SLEP. By allowing for these and other adjustments of the inputs of the model, the DOMICE Simulation Model strengthens ORAM's ability to represent the risk involved with a number of possible deployment and operating scenarios in order to ensure the most effective utilization of USCG assets in Districts 1 and 9.

The model is not 100% accurate; no model is. The inaccuracies in this model likely lead to an overstatement of the economic impact of waterway closures. This inaccuracy is primarily due to the one-week time step in the model, which is based on the weekly reporting of ice data, and which results in the cost of closures being calculated based on week-long intervals. Historically, delays have been addressed in a matter of days. While the model overstates the absolute impact of closures, it does so consistently so that the relative impact (risk) of various force laydowns may be compared to support decision making.

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LIST OF ABBREVIATIONS

AIS	Automatic Identification System
ATON	Aids to Navigation
CGD	Coast Guard District
COTS	commercially available off-the-shelf
D1	USCG District One (northeast)
D9	USCG District Nine (Great Lakes)
DOMICE	domestic ice breaking
dpw-2	USCG District Nine Waterways Management Branch
GPS	Global Positioning System
HHO	home heating oil
LCA	Lake Carriers' Association
MAR	USCG Domestic Icebreaking Mission Analysis Report, released in May 2010
NCDC	National Climactic Data Center
NIC	National Ice Center
NOAA	National Oceanic and Atmospheric Administration
ORAM	Operational Risk Assessment Model
PWCS	Ports, Waterways and Coastal Security
RIN	Risk Index Number
SAR	Search and Rescue
SIGRID	Sea Ice Grid
SLEP	Service Life Extension Program
SME	Subject Matter Expert
USACE	United States Army Corps of Engineers
USCG	United States Coast Guard
WCSC	Waterborne Commerce Statistics Center
WLB	225-foot ice capable buoy tender
WLBB	240-foot heavy icebreaker
WLM	175-foot ice capable buoy tender
WMO	World Meteorological Organization
WTGB	140-foot medium ice breaking tug
WYTL	65-foot light ice breaking harbor tug

1. Background

The United States Coast Guard (USCG) has the statutory authority and responsibility to perform Domestic Ice Breaking (DOMICE) operations and maintain DOMICE facilities and capabilities. Traditional DOMICE operations support search and rescue efforts, flood control, navigation mission areas, and waterborne commerce. The USCG conducts DOMICE operations in the Great Lakes, the Saint Lawrence Seaway, and the coastal and tributary regions of the Northeast and Mid-Atlantic. DOMICE operations primarily occur from December through April, employing 65-foot harbor tugs (WYTL), 140-foot ice breaking tugs (WTGB), 175 and 225-foot buoy tenders (WLM and WLB, respectively), and the 240-foot icebreaker MACKINAW (WLBB). These ice breaking vessels are homeported in the First, Fifth, and Ninth USCG Districts, but may be temporarily relocated between these districts to balance the expected workload. Every winter navigation season, USCG assets must be allocated effectively to meet the demand for ice breaking activities on critical waterways.

The USCG Atlantic Area developed the Operational Risk Assessment Model (ORAM) to more fully account for changes in risk that impact decision-making processes. All six of the following phases in the Homeland Security Risk Management Process are supported by ORAM: (1) define the context of the decision and related goal and objective; (2) identify potential risks; (3) assess and analyze risk; (4) develop and analyze alternatives; (5) decide among alternatives and implement; and (6) monitor the results and use to reassess the context. ORAM is particularly valuable in supporting force apportionment planning processes, with the goal of achieving the most effective distribution of limited USCG assets for meeting operational mission needs. In order to assess various asset distribution options, ORAM was designed to include mission and geographic-specific granularity over an annual planning horizon. The initial modeling within ORAM is complete for the majority of the ten Coast Guard missions that ORAM covers, including DOMICE. The development of ORAM was the product of academic rigor, probabilistic risk analysis, and research, augmented by qualitative assessment by subject matter experts (SMEs) in the absence of data.

The DOMICE Simulation Model was developed to update ORAM and add additional rigor to its analysis capabilities related to the USCG DOMICE mission. In the face of an aging domestic icebreaker fleet, there is a growing need to more fully assess the implications of Service Life Extension Programs (SLEP) and unscheduled maintenance in order to mitigate potential consequences of maintenance-related reductions in ice breaking capabilities. There is also a need to examine further the risk associated with a number of varying conditions that significantly affect DOMICE operations, such as varying levels of winter severity and differences in waterway characteristics. The DOMICE Simulation Model is a tool for the USCG to quantify the risk associated with different ice breaking asset allocation decisions and varying conditions in both operational and natural environments. Additionally, the DOMICE Simulation Model provides a more complete assessment of risk associated with ice breaking activities by analyzing the various levels of impacts incurred from unmet ice breaking demand. Some consequences of insufficient ice breaking activities considered in the model include the economic impacts felt by operators and consumers related to delayed or displaced cargo shipments, as well as the impacts of damages related to ice-induced flooding incidents. By incorporating both these varying conditions and levels of impacts that have been excluded from prior versions of ORAM, the DOMICE Simulation Model allows ORAM to quantify risk with unprecedented levels of detail in order to improve icebreaker deployment strategies in USCG Districts 1 and 9. (The model excludes District 5 because the ice breaking demand is significantly lower there, it is not the homeport of any 140-foot ice breaking tugs, and it does not draw ice breaking resources

2. Project Scope

The DOMICE Simulation Model was developed as a tool to evaluate ice breaking operations in USCG Districts 1 and 9 related to maintaining navigable waterways and removing ice dams to manage flooding. The model draws upon a variety of data sources to quantify risk associated with different deployment assignments of the icebreaker fleet. Risk is measured in terms of the economic impact resulting from asset allocation decisions. The monetized risk calculated by the DOMICE model can be easily integrated into the USCG Operational Risk Assessment Model.

DOMICE model simulations incorporate descriptive information on all District 1 and 9 Tier 1 and Tier 2 waterways, which were defined by stakeholders as "critical waterways" due to either their importance to winter commerce or their susceptibility to winter flooding as a result of an ice jam[1,2]. Detailed modeling within the DOMICE model of specific waterways enables outcome and risk assessment at the District level. Optimization of specific operations and waterways may, however, require more detailed models beyond the scope of this model development effort.

Representative USCG ice breaking assets are considered in the model, as well as relevant Canadian ice breaking assets. Specifically, the following cutter classes are included in the model:

- 240-foot WLBB;
- 140-foot WTGB;
- 65-foot WYTL;
- 225-foot WLB;
- 175-foot WLM; and
- 1050 or 1100 Class Canadian vessels.

The research and development effort involved in the construction of the DOMICE model included the collection, analysis, and migration of available data from a variety of governmental and non-governmental sources. The purchase of data sets or the collection of additional field-level data was beyond the scope of this effort.

3. Objectives

The DOMICE Simulation Model was developed with the objective of incorporating three key factors and sources of variability in a risk analysis of DOMICE operations that were not originally addressed by ORAM. These factors include:

- Winter Severity: The DOMICE Simulation Model was designed to consider winter and ice severity as variable conditions, and to have the ability to simulate the impact of different levels of winter severity;

[1] In December 2009, stakeholders from District 1, District 5, and District 9 grouped all waterways into four tiers, with Tier 1 representing the highest priority and Tier 4 the lowest. Tier 1 and Tier 2 waterways were defined to be "critical waterways" that are either important for winter commerce or susceptible to winter flooding as the result of an ice jam.
[2] USCG. (2010). United States Coast Guard Domestic Icebreaking Mission Analysis Report. May 2010.

- Operational Requirements Specific to Individual Waterways: The DOMICE Simulation Model was designed to account for characteristics specific to individual waterways that affect icebreakers' operational abilities, such as channel depth, width, and probability and degree of icing; and
- Risk Metrics: The DOMICE Simulation Model was developed to use available information on commodity flows and other economic impacts in order to estimate the economic impact of waterway closures. The model utilizes metrics to compare the impacts of the following three main risk drivers: the economic impacts from an inability to ship goods; the consequences of the inability to ship home heating oil to ice-locked communities; and property loss and damage due to ice-induced flooding.

4. Model Overview

The DOMICE Simulation Model considers multiple key factors and varying conditions that affect DOMICE operations in order to assess the implications of decisions regarding the allocation of ice breaking assets. The main output of the model is the risk associated with a particular asset assignment scenario. Risk is quantified in terms of the economic impact incurred as a result of waterway closures, due to the demand for ice breaking activities being unmet by the supply of ice breaking resources. As this description implies, the model must integrate the following three major considerations in order to quantify risk: the range in possible demand for ice breaking activities; the range in possible supply of ice breaking assets; and the range in possible economic impacts incurred when the supply does not satisfy the demand.

Figure 1 demonstrates how the model conceptually integrates these three major components as the following separate, but integrated, modules: the "Ice Breaking Demand" module; the "Ice Breaking Supply" module; and the "Economic Impact" module. The following paragraph summarizes the role of each module in calculating the risk associated with asset assignments.

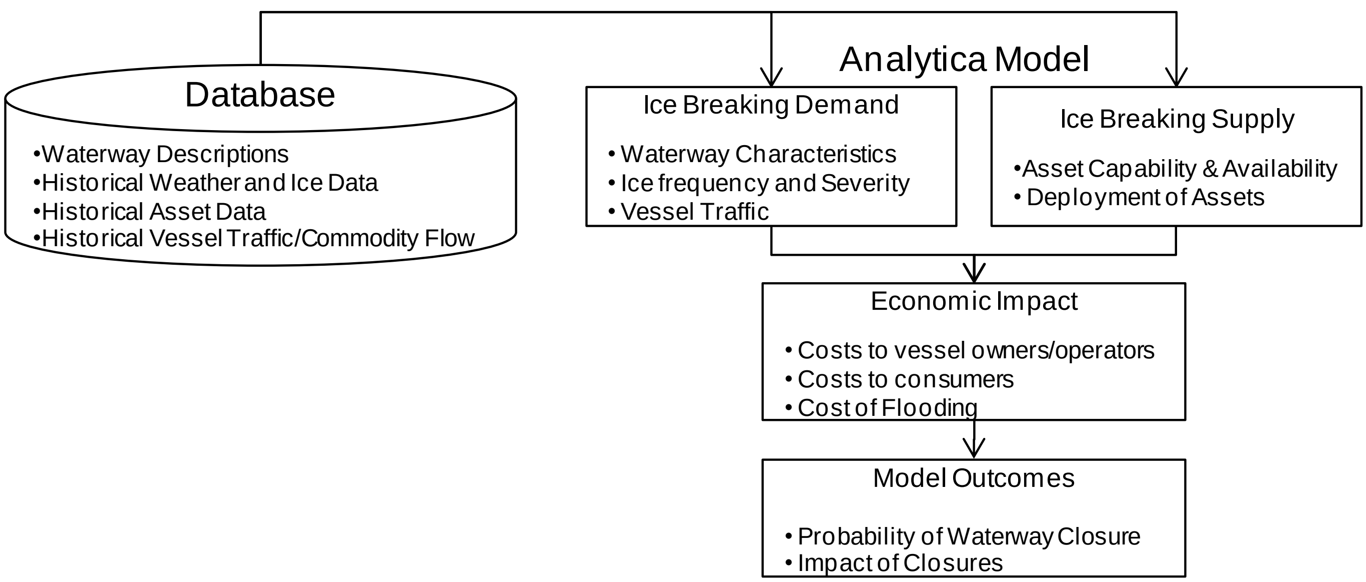

Figure 1. Overview of model information flows.

The "Ice Breaking Demand" module incorporates historical data on ice conditions and vessel traffic flows to assess the demand for ice breaking activities. Waterways form the entities in the demand module, and icing conditions and vessel traffic flow data are specified for each Tier 1 and Tier 2 waterway in District 1 (D1) and District 9 (D9). The "Ice Breaking Supply" module incorporates historical vessel availability rates and SME-identified capabilities of each cutter class to determine the ice breaking capacity provided by a given inventory of assets. U.S. and Canadian ice breaking assets, therefore, constitute the entities in this module. Based on the demand for ice breaking assets and the availability and capability of the specified fleet, the model assigns each asset of the fleet to a specific waterway within a District on a weekly basis. After the allocation process has occurred, waterways in each District may remain closed to vessel traffic for that week due to either there being insufficient ice breaking assets (not enough to go around) or the ice conditions being too severe for the remaining assets to break the ice. The "Economic Impact" module then calculates the economic impacts incurred from the waterway closures each week. Economic impact is calculated based on estimated increases in shipping costs, increased costs to consumers, and the impacts of flooding that may occur in the absence of ice breaking activities. The economic impact of waterway closures can be converted to a Risk Index Number (RIN) and integrated with other USCG ORAM modules. The model's final output of quantified risk allows USCG deployment decisions to be understood in the context of the range of impacts and implications associated with these decisions.

The DOMICE simulation model, created in the commercially available off-the-shelf (COTS) software Analytica, allows for a range in possible risk outcomes to be considered based on variables that affect DOMICE operations. The most significant variables that affect the demand for ice breaking activities involve variations in winter severity and vessel traffic flows. Changes in the inventory of ice breaking assets, as well as varying capabilities and availabilities of these assets, are significant sources of variability in the supply of ice breaking resources. These variations, in combination with variations in the extent of the impact incurred by waterway closures, affect the possible range in the total economic risk associated with DOMICE deployment decisions. The model is structured to allow the user to adjust a variety of conditions in order to observe the risk associated with these changing variables. The user establishes the initial conditions for each simulated ice breaking season. The user can manipulate inputs of the "Ice Breaking Demand" module by selecting winters of varying severity. Additionally, the user can adjust the inputs of the "Ice Breaking Supply" module by choosing alternative deployments of ice breaking assets, and by determining the number and type of ice breaking operations required to maintain a waterway open to vessel traffic.

To further capture these variations and potential ranges in risk outcomes, the model processes multiple types of data through probabilistic simulations to accurately account for the probabilities of the occurrence of events. This probabilistic sampling approach is known as Monte Carlo simulation. Specifically, the model runs multiple iterations for one complete run of the model using the user-specified allocation of assets. Each iteration of the model randomly selects data from a given year, and after many Monte Carlo iterations have been run, the final model outputs reflect probabilistically representative risk profiles associated with that particular inventory of ice breaking assets. For example, if the user selects to run the model based on random years of ice severity data, the model will run the first iteration using weather data from a randomly-selected winter navigation season, followed by a second iteration using another randomly-selected data year, and so on, until the specified number of Monte Carlo iterations have been completed. One simulation run or iteration of the DOMICE model represents one winter navigation season, which is considered to be 20 weeks in duration. The model's sub-processes run on a week-to-week basis in order to capture changing conditions throughout the season.

The following sub-sections will summarize the types of data inputs and processes involved in each of the three main modules.

4.1 Ice Breaking Demand Module

The "Ice Breaking Demand" module determines the demand for ice breaking assets in each District for each week of the winter navigation season. The demand module principally utilizes the probabilistic simulation method described above to process historical weather and vessel traffic data to generate probability distributions for ice conditions and vessel traffic flows on each critical waterway in District 1 and District 9. The output of this module is the total number of hours of ice breaking demand for each cutter class, which is calculated from the number and length of iced waterways and the characteristics of the ice.

One significant challenge in simulating ice severity in the module was due to the lack of consistency in ice data between District 1 and District 9. In District 9, historical ice data was available from the National Oceanic and Atmospheric Administration (NOAA) National Ice Center (NIC) that indicates the type of ice and the maturity, or thickness, of ice on the Great Lakes throughout the winter navigation season. In District 1, however, similar historical ice data was not available, and available data was limited to data on air temperatures and other weather conditions.

To account for these differences in available ice data, a different approach was used to determine ice severity in each District. In District 9, ice reports from 1998 to 2011 were used to determine historical ice characteristics, such as ice type and depth of ice. The probability of these ice characteristics occurring in each critical waterway was determined by probabilistic simulation. In order to create comparability with data from District 9, available data from District 1 was used to correlate air temperatures and precipitation levels to the extent of ice cover. These relationships were used to create regression models to simulate ice severity on waterways in District 1.

Historical vessel traffic flow data is incorporated into the demand module to determine which waterways in each District have a higher demand for ice breaking assets, based on the amount of commercial traffic they support. Vessel traffic, or the number of vessels transiting a waterway, is determined from Automatic Identification System (AIS) data collected by USCG dating back to 2008. The probability of varying levels of traffic flow occurring on each Tier 1 and Tier 2 waterway is determined by selecting historical data through probabilistic simulation. This data informs the ice breaking asset assignment process in the "Ice Breaking Supply" module, which assigns available assets to waterways of high criticality, or commercial importance, before assigning assets to waterways of low criticality.

4.2 Ice Breaking Supply Module

The "Ice Breaking Supply" module determines the total ice breaking capability and availability of the user-specified icebreaker fleet for each week in the ice season, based on the number of available cutter hours and the ice breaking capability of each cutter class. The output of the supply module is the assignment of ice breaking assets to specific waterways in each District for each week of the season.

The main variable of the supply module is the total number of ice breaking assets. Users have the ability to determine the total number of ice breaking assets in a given model run, specifying the number of vessels in each cutter class. The user dictates the distribution of these assets between District 1 and District 9 either for the duration of the entire winter navigation season or for individual weeks of the ice breaking season.

The model's default total number of cutters is based on the "USCG DOMICE Mission Analysis Report (MAR)[3]."

The supply module incorporates characteristics of each cutter class identified by SMEs to represent the ice breaking capabilities of each cutter class. Icebreakers' capabilities are represented in the model primarily in terms of the thickness of ice that each asset is able to break.

Availability rates of assets within each cutter class are another important variable of the supply module. Asset unavailability occurs due to planned or unplanned maintenance, or due to priority assignments of assets to other USCG missions. The total number of possible ice breaking hours used by the module is based on the MAR's assessment of cutter employment during "severe" winters. Although the module's default settings assume that no ice breaking hours are diverted to other USCG missions, the user can adjust the number of hours to affect the availability of each asset type. To reflect unavailability due to maintenance, each cutter class is also assigned a probability of availability based on 2006 through 2009 winter season availability rates, referenced in the MAR.

The supply module uses the inventory, characteristics, and unavailability rates of ice breaking assets to assign assets of each cutter class to specific waterways in each District on a week-to-week basis. Asset assignments follow rules and standard procedures identified by SMEs that relate to deployments in each District. The assignment process also considers the criticality of each waterway to commerce and the type of ice breaking activity required to keep critical waterways open for vessel traffic, whether it be track clearing or track maintenance.

4.3 Economic Impact Module

The DOMICE model uses the outputs from the "Ice Breaking Demand" and "Ice Breaking Supply" modules to determine the number of waterway closures caused per week by the demand for ice breaking activities not being met by the supply of ice breaking assets. The module then calculates the economic impact of the waterway closures, and this total economic impact represents the risk associated with the given deployment scenario.

Several types of economic impacts are used to determine the total economic impact of waterway closures. First, the module factors in increased shipping costs as a result of either shipment delays or shipments being displaced to land-based transportation modes. Secondly, the downstream impact to consumers as a result of shipments being delayed is considered. The types of cargo shipments included in the analysis are shipments of dry bulk goods, liquid bulk goods, perishable goods, and home heating oil that is essential to ice-locked communities. Lastly, the module accounts for potential flooding impacts that may occur in the absence of ice breaking activities.

The estimate of the economic impact due to the closure of a waterway is based on the average typical traffic found on that particular waterway. An analysis of each commercial vessel denied transit in a specific waterway closure is beyond the level of detail included in the module's analysis. Alternatively, AIS data is incorporated in the module to estimate average vessel traffic flows that would be impacted by the closure of the waterway. Data from the United States Army Corps of Engineers (USACE), the Lake Carriers' Association (LCA), and other academic and industry sources are used to determine the monetary value of

[3] USCG. (2010). United States Coast Guard Domestic Icebreaking Mission Analysis Report. May 2010.

each of these impacts. For flooding impacts, the probability of varying amounts of damage due to flooding are calculated using a probabilistic simulation based on historical flooding data.

The final output of this module, and consequently of the DOMICE model, is the risk in terms of the economic impacts of resulting waterway closures associated with the user-specified allocation of assets. Through the DOMICE model's ability to account for multiple varying factors affecting DOMICE operations, the user can also observe the risk associated with these varying conditions, such as variations in winter severity or asset availability.

The following section, Section 5, will examine the model's structure, data inputs, and processes in further detail.

5. Computational Model Description

In order to most accurately represent DOMICE activities, the development of the computational model in *Analytica* required the construction of multiple modules and sub-modules, as well as mapping associated relationships between all facets of the ice breaking mission. This section describes in detail the functions of the modules and sub-modules developed.

The *Analytica* software follows the influence diagram convention, in which a model is represented as a network of connected nodes. Each node is portrayed in dark blue and represents a set of data inputted into the model, some type of model calculation, or model outputs. Each arrow connecting different nodes indicates the direction of influence of one node on another. For instance, an arrow drawn from node A to node B indicates that node A influences node B, or conversely, that node B depends on node A.

Figure 2 provides a conceptual overview of the DOMICE *Analytica* model and the relationships between the main modules. As the arrows between the nodes imply, the calculated "DOMICE Outcomes" depend on both the "Ice Breaking Demand" module and the "Ice Breaking Supply" module. The "Economic Impact" module, also named the "DOMICE Economic Impact" module, impacts both the Supply and Demand modules. Section 5.1 will define general factors related to the scope of the DOMICE model. Sections 5.2, 5.3, and 5.4 will describe individually the three main modules of the model and their corresponding sub-modules in detail. Section 5.5 will discuss the outcomes of the DOMICE model.

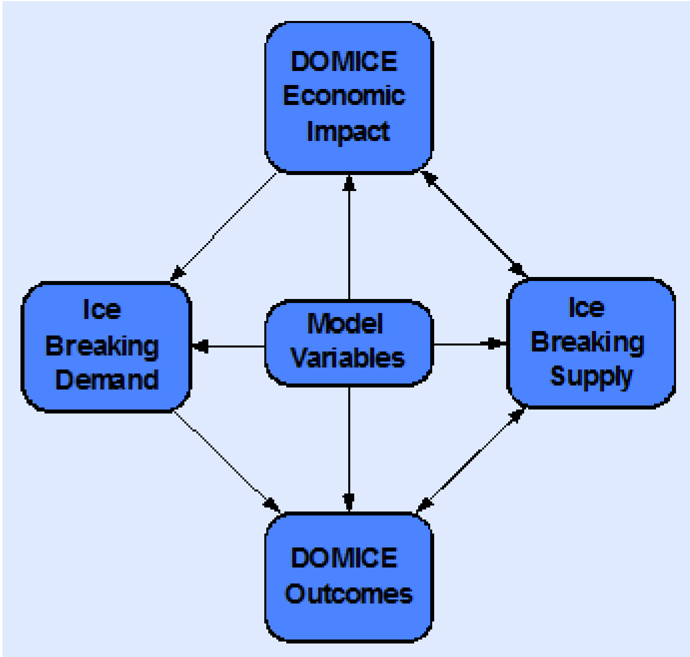

Figure 2. Overview of the DOMICE model.

5.1 Model Scope

As Figure 2 above indicates, the “Ice Breaking Demand” module, the “Ice Breaking Supply” module, the “Economic Impact” module, and the “DOMICE Outcomes” are all defined in terms of common “Model Variables.” These “Model Variables” are used consistently throughout the sub-modules and refer to factors that define the scope of the DOMICE model. These factors include: Districts; waterways; and the duration of the winter navigation season.

Many of the sub-modules require waterways and ice breaking assets to be identified at the District level. The Districts considered by the model are District 1 on the East Coast and District 9 on the Great Lakes. District 5, in the Mid-Atlantic region, is not included in the model’s analysis because it is significantly less likely to experience a severe winter and does not share in the pool of 140-foot ice breaking tugs homeported in Districts 1 and 9. While the user can change asset assignments from one District to the other, the distinction between District 1 and District 9 waterways and ice breaking assets is preserved throughout the processes of the DOMICE model.

The waterways considered in the DOMICE analysis are constant within all sub-modules, and each waterway is assigned to one of the two Districts. Only Tier 1 and Tier 2 waterways are considered in the analysis. The model does not distinguish between the tiers but assigns ice breaking assets based on “demand” as determined by the presence of ice and the level of traffic. Table 1 lists all of these waterways, as well as the waterway systems to which they pertain, for each District.

Table 1. Tier 1 and 2 waterways in District 1 and District 9.

District 1		District 9	
Waterway	**Length (miles)**	**Waterway**	**Length (miles)**
Kennebec River	15.0	Eastern Lake Erie	15.0
Piscataqua River	7.5	Georgian Bay	8.7
Penobscot System	45.0	Lake Ontario	81.0
Penobscot Bay	25.0	Lower Green Bay	33.0
Penobscot River	22.0	Upper Green Bay	37.0
Portland Waterway System	5.0	Saginaw Bay	16.5
Casco Bay	4.0	Southern Lake Michigan	12.0
Fore River	1.0	St. Lawrence River	25.0
Weymouth Fore River System	19.8	Thunder Bay	15.6
Boston Harbor	10.0	Western Lake Superior	12.0
Town River	1.5	Straits of Mackinac System	52.3
Weymouth Fore River	7.0	Grand Traverse Bay	7.3
Weymouth Back River	1.3	Straits of Mackinac	45.0
Narragansett Bay Waterway System	34.1	Sault St. Marie Waterway System	62.5
Narragansett Bay	10.1	Upper St. Mary's River	52.1
Providence River	13.7	Middle Neebish	4.8
Mount Hope Bay	10.3	West Neebish	5.6
Cape Cod Canal Waterway System	23.0	Detroit Waterway System	37.0*
Cape Cod Canal	8.0	Detroit River	6
Buzzard Bay	15.0	Lake St. Clair	22
Nantucket Waterway System	9.0	St. Clair River	9
Vineyard Haven Harbor	1.5	Maumee Bay/Pelee Passage System	16.7
Lewis Bay	2.0	Maumee Bay	8.5
Nantucket Harbor	7.0	Pelee Passage	8.2
New Haven System	13.6		
Thames River	3.5		
Connecticut River	3.6	*Estimated length of ice breaking	
New Haven Harbor	2.5		
Bridgeport	2.0		
Port Jefferson	2.0		
Hudson River Waterway System	66.0		
Upper Hudson River	28.0		
Middle Hudson River	38.0		
Newark Waterway System	20.0		
Arthur Kill Channel	16.0		
Newark Bay	4.0		
Manhattan Waterway System	64.0		
Lower Hudson River	57.0		
East River Connector	7.0		

Time is defined in the model as each week[4] of the winter navigation season, which is assumed to be 20 weeks long. Table 2 demonstrates the dates associated with each of the 20 weeks. The "Sub-Seasons in D9" column applies only to the winter navigation season in District 9, and indicates the weeks in which the major Great Lakes interconnecting waterways are closed to navigation. The following three winter navigation periods are defined for the Great Lakes winter ice season[5]: Extended Navigation, or open shipping from December 15th to January 20th; closed navigation, or reduced shipping from January 20th to March 10th; and Spring Breakout, or open shipping from March 10th to April 30th.

Table 2. Weeks of the winter navigation season.

Week	Week Begins	Week Ends	Sub-Seasons in D9
1	15-Dec	21-Dec	Extended Navigation
2	22-Dec	28-Dec	Extended Navigation
3	29-Dec	4-Jan	Extended Navigation
4	5-Jan	11-Jan	Extended Navigation
5	12-Jan	18-Jan	Extended Navigation
6	19-Jan	25-Jan	Closed
7	26-Jan	1-Feb	Closed
8	2-Feb	8-Feb	Closed
9	9-Feb	15-Feb	Closed
10	16-Feb	22-Feb	Closed
11	23-Feb	29-Feb	Closed
12	1-Mar	7-Mar	Closed
13	8-Mar	14-Mar	Spring Breakout
14	15-Mar	21-Mar	Spring Breakout
15	22-Mar	28-Mar	Spring Breakout
16	29-Mar	4-Apr	Spring Breakout
17	5-Apr	11-Apr	Spring Breakout
18	12-Apr	18-Apr	Spring Breakout
19	19-Apr	25-Apr	Spring Breakout
20	26-Apr	2-May	Spring Breakout

5.2 Ice Breaking Demand Module

The "Ice Breaking Demand" module incorporates waterway-specific ice data and vessel traffic data to determine the demand for ice breaking assets on each waterway for each week of the winter navigation season. The module consists of two main sub-modules. One sub-module is used to process ice data in order to determine whether ice would impede normal vessel traffic on specific waterways each week, in the absence of ice breaking assets. The other sub-module is used to process vessel traffic data in order to prioritize ice breaking activities by ranking waterways in order of their commercial importance.

[4] The model's weekly time step was chosen based on the availability of ice severity data. This time step may overstate the total DOMICE risk. For example, if there is a waterway closure for two days, the model would consider the waterway closed for the entire week.
[5] USCG. (2009). Ninth District Domestic Icebreaking Policy and Procedures, D9INST M16150.2B. Ninth Coast Guard District: Cleveland, Ohio.

5.2.1 Ice Conditions Sub-Module

The sub-module uses historical ice data to determine on a weekly basis the maximum thickness of ice present on each waterway, which is characterized by the type of ice present. Table 3 indicates the three categories of ice types used to characterize maximum ice thickness throughout the DOMICE model. Based on the maximum thickness of each type of ice in the waterway, the sub-module determines whether the ice would impede normal traffic on each waterway in the absence of icebreakers, and whether the various types of icebreakers would be capable of breaking the maximum thickness of ice present on each waterway. (The model does not account for localized ice ridges, but by rule assigns appropriate resources where ridges are most problematic, for example, assigning the 240' WLBB to the Detroit River System.)

Table 3. Types of ice and associated ice thickness (feet).

Types of Ice	Range of Ice Thickness (feet)
Solid level ice	0 to 4
Loose brash ice	0 to 1
Packed brash ice	0 to 4

Depending on the District, each waterway's ice characteristics and ice data are either defined or modeled for each week of the ice breaking season. As discussed previously, disparities between the types of ice data available for each District required the sub-module to use statistical ice simulation models to determine ice thickness in District 1, whereas historical ice data was used to determine ice thickness in District 9.

For District 9, the determination of ice thickness on each waterway is based upon historical ice data from the fall of 1998 to the spring of 2011. To account for variability in ice thickness, the model allows the user either to select a specific year of District 9 historical ice data, such as ice data for the ice season 2008 to 2009, or to randomly select a year's ice data for each Monte Carlo iteration.

The NOAA National Ice Center generates weekly or semi-weekly ice reports for the Great Lakes. Discrete Global Positioning System (GPS) coordinates are used to define the geometric "shape" of the ice cover in the Great Lakes, and a list of attributes is provided to characterize the ice within the outlined area. These attributes are described in terms of ice codes recorded as Sea Ice Grid (SIGRID) code values established by the World Meteorological Organization (WMO). The DOMICE ice conditions sub-module converts the SIGRID ice codes to the feet of ice thickness present on each waterway, as indicated by Table 4. Once the thickness of ice on a given waterway is determined, the sub-module can characterize the ice in terms of thickness of each of the three types of ice to determine if the ice would impede vessel traffic.

Table 4. Conversion of SIGRID ice codes to feet of ice thickness.

Stage of Development	SIGRID Ice Codes	Equivalent Feet of Ice Thickness
Ice Free	00	0.00
No Stage of Development	80	0.00
New Ice	81	0.00
Nilas, Ice Rind	82	0.33
Young Ice	83	0.98
Grey Ice	84	0.49
Grey-White Ice	85	0.98
First Year Ice	86	6.56
Thin First Year Ice	87	2.30
Thin First Year Stage 1	88	1.64
Thin First Year Stage 2	89	2.30
For Later Use	90	0.00
Medium First Year Ice	91	3.94
For Later Use	92	0.00
Thick First Year Ice	93	5.00
For Later Use	94	0.00
Old Ice	95	0.00
Second Year Ice	96	0.00
Multi-Year Ice	97	0.00
Glacier Ice	98	0.00
Undetermined/Unknown	99	0.00

Note: Codes 95 through 98 set to zero as Great Lakes ice is always first year.

Unlike in District 9, there is no quantitative data currently available in District 1 that measures the ice thickness on critical waterways in past winter navigation seasons. The only information available for ice conditions consists of USCG ice reports that, while useful in validating the model's results, are qualitative in nature and cannot be quantified in a meaningful way for input into the model. Because of these restrictions in data availability, historical meteorological data is used to simulate past ice conditions in District 1. Specifically, the sub-module uses air temperature as an indicator of ice formation[6]. Regression models were created to first correlate District 9 historical air temperatures with District 9 historical ice data, and then to correlate this relationship to the model-sampled or user-selected historical air temperature data for District 1 waterways. By modeling this relationship between air temperature and ice thickness, the thickness of ice that would be present on each District 1 waterway is simulated based on the air temperature data. The District 1 weather-ice regression models include both linear terms for the influence of air temperature on ice formation and probabilistic error terms for regression residuals in which ice formation is not explained by the linear terms. The District 1 weather-ice regression models are defined for each week in the ice season, in order to better simulate the time-series profile of ice formation over the course of an ice season.

[6] White, K. (2004). Method to Estimate River Ice Thickness Based on Meteorological Data. Ice Engineering. Hanover, New Hampshire, U.S. Army Engineer Research and Development Center Report. ERDC/CRREL Technical Note 04-3.

In addition to the thickness of each type of ice, the model accounts for a separate dimension of weather severity. Approximately one ice season in ten is regarded as severe. For example, the 2002 to 2003 ice season was regarded as a severe winter in District 9. For both Districts, but primarily in District 1, variability in the severity of ice conditions is incorporated into the sub-module by using severity-dependent assignment rules. Ice severity is determined by the sub-module based on the District. Ice conditions in District 1 are considered "severe" if the sub-module indicates that the Cape Cod Canal is iced over for a week[7]. In District 9, ice conditions are considered "severe" if either the sub-module or the user sets the ice data year to 2003, or in other words, selects the 2002-2003 ice season.

5.2.2 Vessel Traffic Sub-Module

The second sub-module of the "Ice Breaking Demand" module utilizes historical vessel traffic data to determine the relative importance of waterways in terms of the vessel traffic flow that they support. The waterway that is transited by the most commercial vessels over the course of the ice season is considered the waterway with the highest priority for ice breaking activities. Based on historical AIS data inputs, the sub-module assesses the number of unique vessels transiting a waterway each day of each week of the winter navigation season. The number of unique daily transits is combined to determine the total number of vessel passes through a waterway over the course of an ice season. The sub-module accounts for the probability of varying levels of traffic flow through a probabilistic simulation based on historical data.

Inputs from the "Economic Impact" module, which will be described in detail in Section 5.4, are used within the vessel traffic sub-module to determine the criticality of each waterway in terms of the value of economic commerce moving through each waterway. Waterway criticality affects the demand for ice breaking assets in each District, and therefore, is an important component of the "Ice Breaking Demand" module. As an example of the interconnected structure of the DOMICE model, water criticality is also an important input used by the "Ice Breaking Supply" module in determining the assignment of ice breaking assets to waterways.

5.3 Ice Breaking Supply Module

Figure 3 shows the design of the "Ice Breaking Supply" module, which examines the availabilities and capabilities of the icebreaker fleet. Several kinds of information are included regarding ice breaking assets, such as: the inventory of icebreaker vessels in the fleet; the functional characteristics of each cutter class; and the unavailability rates of the assets due to other USCG missions and unplanned maintenance. Each of these factors is processed through a sub-module of the "Ice Breaking Supply" module and will be discussed separately here. The module uses these types of information on vessel characteristics, along with ice data from the demand module, to calculate whether a particular type of ice breaking asset would be capable of breaking the ice present in each waterway for a given model run. Each vessel's capabilities and availabilities within a specific model scenario are used to determine the allocation of ice breaking vessels to waterways in each District.

[7] This definition of a "severe" winter season in District 1 is based on SME input collected in a DOMICE stakeholder meeting.

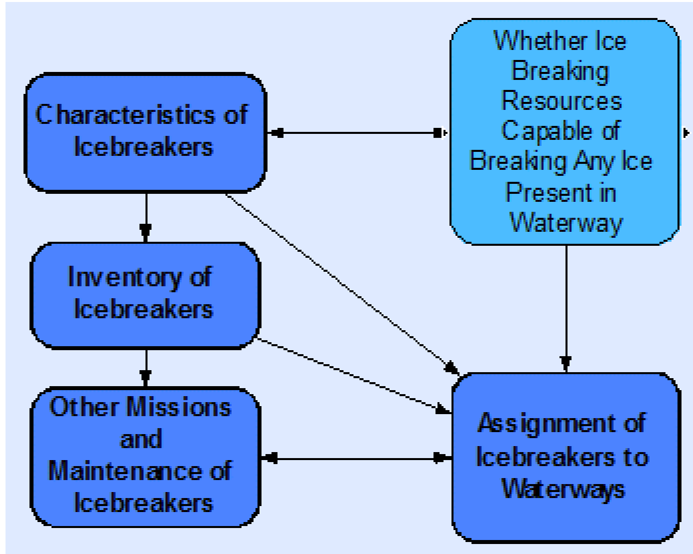

Figure 3. Ice breaking supply.

Table 5 presents the baseline inventory of icebreakers considered in the DOMICE model, as part of the "Inventory of Icebreakers" sub-module. The location of each ice breaking asset is defined in terms of the District to which it is assigned and the overall inventory of icebreakers available during the ice breaking season. The user can manipulate the baseline inventory of icebreakers to assign any asset to one of the two Districts for the winter navigation season and can additionally adjust the inventory of available icebreakers in each District on a week by week basis. As Table 5 indicates, both ice breaking assets of the US domestic fleet and of the Canadian fleet are considered. The inventory of ice breaking assets is specified to the number of vessels per vessel class available for deployment, and does not include an assessment of unique characteristics or abilities of individual vessels within each vessel class.

Table 5. Baseline inventory of icebreakers.

Type of Icebreaker	East Coast (District 1)	Great Lakes (District 9)
240'-WLBB (Heavy)	0	1
140'-WTGB (Medium)	3	6
65'-WYTL (Light)	8	0
225'-WLB (Ice capable)	2	2
175'-WLM (Ice capable)	4	0
1050 or 1100 (Canadian)	0	2

The "Characteristics of Icebreakers" sub-module incorporates a variety of factors that affect the capability of assets to break ice as assessed by SMEs. For each type of vessel, the sub-module defines ice breaking capabilities in terms of a vessel's ability to break the three identified types of ice. Both the speed at which an icebreaker can operate and the number of passes needed per week to maintain a waterway open to traffic depend on the type of clearing activity conducted. Specifically, two types of clearing activities are considered, namely, direct/clearing of the waterway (directly escorting one or more vessels or first time through unbroken ice in a waterway) or indirect/preventative clearing (maintaining an existing track). Weather conditions also impact the type of clearing activity conducted, which in turn depend on the District to which the waterway pertains. Two types of weather conditions are considered, namely “moderate” or “severe” conditions, as discussed previously in Section 5.2. Table 6 indicates the speeds assigned to icebreakers in the sub-module. Table 7 shows the number of passes needed per week in District 1 to maintain a waterway open to vessel traffic, depending on the severity of weather conditions and the type of clearing activity conducted. Due to the higher variation in ice breaking activities in District 9 than in District 1, the number of passes required per week in District 9 varies by waterway and by time of the year. For most D9 Tier 2 waterways, the number of passes is directly related to the number of vessels transiting the waterway. The sub-module assumes that two passes are required per day of vessel transit in moderate winters and that three passes per day of vessel transit are required in severe winters. D9 Tier 1 waterways require 14 to 21 passes per week during the Extended Navigation and Spring Breakout seasons, while closed season requirements are tied directly to vessel traffic.

Table 6. Icebreaker speeds (in knots).

Possible Severities of Weather Conditions	Icebreaker Speeds on East Coast (District 1)	Icebreaker Speeds on Great Lakes (District 9)
Moderate	5	3
Severe	5	2

Table 7. District 1 number of passes needed per week.†

Type of Clearing Activity	Moderate Weather Conditions	Severe Weather Conditions
Clearing / Direct	1-2	1-7
Preventative / Indirect	4-10	7-14

†The number of passes required is deterministic; however, it varies over the length of the season.

Transit time is also considered a characteristic of icebreakers, representing the number of days required for a vessel to be dispatched from one waterway to another. Transit time is typically one or two days, depending on the type of icebreaker and the District. Table 8 indicates the baseline transit times considered for each vessel class in each District, which can be adjusted by the user.

Table 8. Transit times (in days).

Icebreaker Type	Number of Days due to Transit on East Coast (District 1)	Number of Days due to Transit on Great Lakes (District 9)
240'-WLBB (Heavy)	1	1
140'-WTGB (Medium)	1	1
65'-WYTL (Light)	2	1
225'-WLB (Ice capable)	2	1
175'-WLM (Ice capable)	1	1
1050 or 1100 (Canadian)	1	1

Table 9 demonstrates the capabilities of the icebreaker classes in terms of the thickness of each type of ice that they are able to break. (The table reflects SME judgments of icebreaker capabilities "as practiced," a modification of the capabilities presented in the DOMICE MAR.)

Table 9. Icebreaker capabilities in breaking three types of ice.

Cutter Class	Cutter Type	Solid Level Ice	Loose Brash Ice	Packed Brash Ice
WLBB	Heavy	Over 24 inches	Up to 9 feet	Up to 9 feet
WTGB	Medium	Up to 24 inches	Up to 6 feet	Up to 6 feet
WYTL	Light	Up to 12 inches	Up to 3 feet	Up to 1.25 feet
WLB	Ice capable buoy tender	Up to 14 inches	Up to 3 feet	Up to 3 feet
WLM	Ice capable buoy tender	Up to 10 inches	Up to 1.25 feet	Up to 1.25 feet

The "Other Missions and Maintenance of Icebreakers" sub-module accounts for the probability of a vessel being unavailable for ice breaking activities. Two causes for icebreaker unavailability are considered in the module, namely, asset unavailability due to maintenance downtime and asset unavailability due to assets being assigned to other USCG missions as priority over ice breaking for commercial traffic. Based on the calculated number of available cutter hours and the capability of each cutter class, total available ice breaking availability is calculated for each week in the ice season.

The sub-module determines the unavailability of assets due to maintenance based on the historical availability data from the "USCG DOMICE Mission Analysis Report," presented in Table 10 below as the percent of time each asset is free from major casualties. The 240' WLBB had 100 percent availability rates in each of the three years since it entered service, but the MAR establishes only a 95 percent availability target for each vessel class. In the sub-module, it was assumed that the 240' WLBB would have a 100 percent availability probability half of the time and a 95 percent availability the other half of the time. The model randomly assigns availability for other classes based on the historic rates table.

Table 10. Historical availability rates.

Cutter Class	2006	2007	2008	2009
WLBB	-	100%	100%	100%
WTGB	77.4%	67.7%	77.1%	81.2%
WYTL	66.5%	72.7%	94.6%	93.2%
WLB	51.2%	55.8%	56.2%	71.7%
WLM	77.1%	71.0%	55.7%	55.6%

As for unavailability of assets due to other USCG missions, the default settings of the sub-module assume that there are no missions, whether Aids to Navigation (ATON), Ports, Waterways and Coastal Security (PWCS), or Search and Rescue (SAR), that demand enough hours while there is a demand for ice breaking to significantly reduce the availability of assets for breaking ice. The sub-module can be adjusted, however, to assign hours of icebreaker assignments to these other missions at the user's discretion. (The adjustments may be made probabilistically over the course of the season or adjusted on a week-by-week basis, as discussed previously.)

The three sub-modules described above each impact the "Assignment of Icebreakers to Waterways" sub-module, which assigns vessels of each cutter class to specific waterways for each week of the winter navigation season. Several inputs from other modules discussed previously are used to influence asset allocation. Several ice-related variables from the "Ice Breaking Demand" module are inputted in order for the sub-module to determine which waterways need ice breaking in each District. The number of assets of each cutter type available for ice breaking each week is calculated using the total inventories of ice breaking assets (which accounts for planned maintenance or assignments to other missions) and the probabilities that any asset would be unavailable for ice breaking due to unplanned maintenance or other mission assignments. This consideration is important because assets in each District are assigned only to waterways in that District. Other factors are used to determine the number of vessels necessary to perform the required number of passes per week in a particular waterway. This ice breaking need depends on:

- The speeds at which vessels perform either track maintenance or direct/active clearing, as well as the requisite number of passes for track maintenance or direct/active clearing;
- The number of daylight hours and number of working days in the week. The module assumes that there are seven working days per week during the ice breaking season;
- Transit times, if applicable; and
- Whether assigned icebreakers were sufficient to perform continuous track maintenance in the waterway the previous week or whether the ice has been cleared at least once in the current week.

In addition to these factors, the "Assignment of Icebreakers to Waterways" sub-module allocates ice breaking assets to waterways based on two types of conditions or rules. "Static Assignment Rules" and "Assignment Rules Dependent on Vessel Type and Clearing Activity" are followed by the sub-module to determine the sequential application of vessel assignments in an order that reflects assignment priorities within each District.

5.3.1 Static Assignment Rules

As discussed briefly in Section 5.2, waterways are generally prioritized in the DOMICE model to reflect the value of commercial goods transported on each waterway. However, as a higher priority above the commercial criticality of waterways, the "Assignment of Icebreakers to Waterways" sub-module prioritizes certain waterways for asset assignments based on a series of advance assignments of assets. These conditions, or "static assignment rules," were determined from consultations with SMEs for each District. The sub-module considers advance assignment of icebreakers and time-dependent and weather-dependent rules to determine the allocation of assets. Once these assignments have been made, remaining assets are assigned to waterways based on their commercial importance.

These assignments are made without considering factors that affect waterway priority in subsequent assignments, such as commercial vessel traffic. Prior to making the assignments, the sub-module checks whether available inventories allow the advance assignments to be made. Several examples of these rules for advance assignments for District 1 include:

- From December 20 (Week 2) to February 28 (the end of Week 11), one 140' icebreaker is dispatched to clear ice in the upper Hudson River, also referred to as the Hudson River System; and
- From January 10 (Week 5) to February 15 (the end of Week 9), one 140' icebreaker is dispatched to clear ice in the lower Hudson River, also described as the Manhattan River System;
- On March 15 (Week 14), one 140' icebreaker is dispatched to the upper Hudson, also described as the Hudson River System, for preemptive flood control operations;

- On March 15 (Week 14), two 65' icebreakers are dispatched to the Kennebec and Penobscot Rivers for preemptive flood control operations.

Some of these advance assignments are based upon time and weather-dependent assumptions for each District. For example, there are some periods of time in District 1 that are known to only require icebreakers to perform indirect ice breaking, or track maintenance,. There are also time periods in which specific waterways are allowed to ice over in District 9, such as part of Green Bay during the closed navigation period. These considerations are included in the sub-module. If applying all of the above rules for each week results in assignments that do not exceed the numbers of available icebreakers of a particular cutter class, then the sub-module proceeds to make all of the corresponding assignments. Otherwise, if only the weather-independent advance assignments can be made without exceeding available inventories, then the module makes only these assignments. If no advance assignments can be made due to limitations in availability of a particular type of icebreaker, then the module makes no advance assignments of that type of asset.

5.3.2 Assignment Rules Dependent on Vessel Type and Clearing Activity

For each week of the ice season, the “Assignment of Icebreakers to Waterways” sub-module considers whether to assign one or two icebreakers of a particular icebreaker class, such as 65s or 140s, to perform either track maintenance or direct clearing in a waterway. The sub-module makes these successive assignments of any remaining assets only after having met the requirements of the “Static Assignment Rules.” Assignments can be made to waterways that satisfy all of the following conditions:

Ice is present in a waterway and the specified vessel type is capable of breaking the thickness of ice present in the waterway;

- Assets remain available after the previous assignment;
- Assets would be sufficient for clearing the length of a waterway with the required number of passes per week. If one asset would be sufficient to clear the length of a waterway, then one asset would be assigned, but if two assets would be needed to clear the length of a waterway, then two assets would be assigned;
- Either track maintenance or direct/active clearing would be an appropriate activity in the current week. This would exclude, for instance, waterways in which track maintenance is not performed during the closed season in District 9; and
- The waterway is the highest assignment priority among the set of waterways that both meet all of the above conditions and do not yet have an appropriate icebreaker assigned to them. Priority reflects advance assignment rules, as well as commercial importance of waterway traffic. In District 9, priority also reflects the Search and Rescue (SAR) standby duty rules.

The SAR standby duty requirements are used in the sub-module when establishing the first priority of any given waterway for asset assignment in District 9. SAR standby duty requirements and the length of time dedicated to each SAR standby duty were determined according to the SAR Guard rules written in the "Cleveland SAR Plan[8]” and the "Heavy Weather Plan.” The following two statements from these documents are examples of the requirements to which the sub-module adheres:

[8] USCG. Cleveland SAR Plan. CCGD9 INST M16100 (series).

- "From November 1st to April 1st, [District] Nine Waterways Management Branch (dpw-2) shall assign cutters to Lake SAR Standby for Lakes Erie, Huron, Michigan, and Superior;"
- "[District] Nine (dpw-2) will not normally assign SAR Standby for Lake Superior during the closed navigation season, nor for Lake Ontario;"

The modeled SAR standby requirement rules indicate, for each week and for each step in the assignment process, whether:

- Assets are subject to SAR Standby requirements that week; and
- There are not yet any assets assigned to each SAR Standby Area. There are five SAR Standby Areas in District 9, which include the Lake Superior Area, the Lake Huron Area, the Lake Michigan Area, the Lake Erie Area, and the Lake Ontario Area.

The sequential assignment of assets is performed through a series of separate sub-modules, with each sub-module designed for a specific cutter class and a specific type of ice breaking activity. For instance, the assignment of 65s to track maintenance has a separate sub-module than the assignment of 140s to track maintenance. Similarly, the assignment of 65s to active/direct clearing has a separate sub-module than the assignment of 65s to track maintenance. Vessel assignments are determined one asset or one pair of assets at a time in each District, in order to avoid exceeding available inventories of assets in the District. Once an assignment of one asset or one pair of assets is made, the module proceeds to consider making another assignment of the same type of asset. If all of the above conditions are not met by that asset type, the module does not make any more assignments of assets of that cutter class and, instead, considers the vessels of the next asset type. Once the module has made assignments for all the available assets in the current week, it then proceeds to determine assignments for the following week.

The icebreaker assignment sub-modules consider the assignment of assets to track maintenance separately from assignments for direct clearing. The sub-modules also consider the timing of assignments when considering maintenance assignments. For each week, the sub-modules consider assignments in the following order:

1. Assignment of assets to maintain any tracks where track maintenance was being performed in the previous week;
2. Assignment of assets to active clearing needed this week; and
3. Assignment of any remaining assets to maintain tracks that are being cleared this week.

At each of the numbered steps above, the assignment sub-modules also consider each class of ice breaking asset in a specific order that reflects icebreaker class capability, the need to focus the most capable assets to the waterways in which their capabilities would be put to greatest use, and the practical limitations of the 175' WLM. The 240 is assigned first by the sub-modules, and is usually assigned either to the Sault Ste. Marie System or the Detroit River System. The assignment of 65s is considered second, followed by the assignment of 140s. The Canadian assets, which are 1050s or 1100s, are considered for the next assignments. Lastly, the 225s and 175s are assigned, with 175s being the last cutter class considered. The 225s and 175s are the final vessels considered for assignment due to their role as backups to other assets in the fleet and to ensure that these assets are only used if all vessels of other cutter classes are not able to meet ice breaking needs.

The successive assignment of assets to waterways is implemented in each sub-module using a series of vertically repeating assignment steps. This structure allows the sub-module to function in a way similar to that of calculations organized in a single column of a spreadsheet. For example, the second assignment step following the assignment of the 240, is for the first sequential assignment of available 65s to maintain any tracks where track maintenance was being performed the previous week. The calculations specific to that assignment step are organized horizontally. The calculations specific to the second assignment are found in the second row, and so on. Enough sets of calculations are provided to allow for up to ten assignments of 65s to a particular type of ice breaking activity, such as track maintenance, which exceeds the inventories of 65s in either District.

The final output of the “Assignment of Icebreakers to Waterways” sub-module is the number of assets of each cutter class assigned to each waterway for each week in each District. As a means of confirming that the resulting number of icebreakers assigned is reasonable, the sub-module compares the total number of assets assigned to the total number of assets available for assignment. If the number of assets assigned does not exceed the total number of available assets for assignment, the module’s results are validated.

5.4 Economic Impacts of Unmet Ice Breaking Demand

The outputs from the “Ice Breaking Demand” and “Ice Breaking Supply” modules are used to determine the length of time a waterway would remain closed to vessel traffic as a result of the demand for ice breaking activities being unmet by the supply of available ice breaking assets. The third module, or the “Economic Impact” module, calculates the economic impact of the waterway closures that occur in an ice breaking season due to this unmet demand. Economic impact is calculated based on two main types of impacts, namely, cargo shipping impacts and flooding impacts. The module’s output is the total economic impact of waterway closures for the entire season, which reflects the risk associated with DOMICE activities.

5.4.1 Cargo Flow

The “Economic Impact” module contains sub-modules that determine from historical data the average cargo volume transported per vessel during the winter navigation season in District 1 and in District 9. Three data inputs are used to determine these values: historical AIS data indicating vessel traffic flows; data on cargo volumes transported on each waterway, provided by USACE’s Waterborne Commerce Statistics Center (WCSC) and the LCA; and economic values of cargo transported, obtained from the US Economic Census.

Table 11 lists the cargo types considered in the module. The module groups the four types of cargo into two broader categories, namely, Home Heating Oil (HHO) shipments or Non-HHO shipments.

Table 11. Cargo types.

Types of Cargo	Cargo Group
Dry Bulk	Non-HHO
Liquid Bulk	
Perishable / Food	
Home Heating Oil	HHO

The data from the USACE and LCA are used to determine the average amount of each type of cargo, in metric tons, transported on each waterway for each week of the winter navigation season. Average cargo loads are divided by the estimated number of vessels transiting each waterway during each week of the ice breaking season to determine the average cargo load transported per vessel. This level of analysis determines the average load of cargo transported across all vessel types, and does not attempt to quantify specific cargo load for each type of commercial vessel transiting waterways.

From the average cargo loads determined per vessel, US Economic Census data is used to calculate the economic value of cargo transported on each waterway for every week of the winter navigation season. The value of cargo transported is used by the sub-module only to determine the criticality of each waterway, which in turn feeds into the "Ice Breaking Demand" and "Ice Breaking Supply" modules. It should be noted that while the "Economic Impact" module contributes to determining waterway criticality, waterway criticality is not involved in the calculation of the total economic impact of waterway closures. The determination of waterway criticality based on the commercial importance of each waterway is used exclusively in determining the demand for ice breaking activities and prioritizing the allocation of ice breaking assets to the waterways that have greater ice breaking demand.

5.4.2 Determination of Waterway Closure

Once the assignments of ice breaking assets to waterways have been made by the "Ice Breaking Supply" module for each week in each District, a "Waterway Closure" table is generated in the "Economic Impact" module. The table tracks which of the Tier 1 and Tier 2 waterways are closed for that week in each District. Waterways are closed if either the thickness of ice on the waterway could not be broken by the assets available, or if there were not enough ice breaking assets to be assigned to that waterway for the week.

5.4.3 Calculation of Economic Impact

Impacts of waterway closures related to cargo impedance and flooding are considered in the economic valuation of the impact of waterway closures in the module. Specifically, sub-modules calculate the costs incurred from the three following major types of impacts: initial impacts of cargo impedance; downstream impacts of cargo impedance on consumers; and flooding impacts occurring in the absence of ice breaking activities.

5.4.3.1 Initial Impacts of Cargo Impedance

An assumption of the module is that a shipment of cargo impeded by a closed waterway will either be delayed until the waterway is re-opened before proceeding to its final destination, or the cargo will be re-routed to an alternative mode of transportation, such as highway transport. In the first case, cargo vessels still have the capacity to transport the amount of shipment delayed, whereas in the second case, vessel capacity is exceeded by the quantity of delayed shipments, causing these shipments to be shipped by alternative modes of transportation. Both options incur unique costs. The sub-module either assigns "Operating Costs" or "Alternative Shipping Costs" to an impeded shipment. Operating cost impacts include the cost incurred by vessel owners or operators while waiting for the waterway to be reopened. Alternative shipping costs considers the increased cost of offloading goods at an intermodal port and loading them onto overland transportation means.

Due to the greater availability of commercial vessels and lack of distinct navigation seasons in District 1, all commercial cargo, except home heating oil, is assumed to be delayed while waiting for the waterway to reopen. Due to the critical nature of home heating oil, all home heating oil is rerouted to overland transportation, specifically by truck, for distribution to the surrounding area.[9] The model lacks the fidelity to accurately predict the critical resource decisions made by D1 in the face of insufficient icebreaking resources. For example, within Tier 1 and 2 waterways, D1 prioritizes resources to facilitate critical HHO deliveries (e.g., up the Hudson, through the Cape Cod Canal, and to island communities). The model does not include that refinement.

District 9 experiences a much greater constraint than District 1 due to the relatively fixed size of the fleet of commercial vessels operating in the lakes, known as "Lakers," during an ice season. Initially, cargo is assumed to be delayed and costs are borne by the vessel owners or operators.[10] Once the cumulative level of impeded cargo exceeds the spare capacity of the Laker fleet, the model reroutes the cargo to overland routes and assigns costs associated with the increased cost of overland transport, as seen in Table 12.

Table 12. Alternative shipping mode costs.

Types of Cargo	Alternative Shipping Mode Increased Cost per Ton
Dry Bulk	\$9.35 - 32.49†
Liquid Bulk	\$9.35 - 32.49†
Perishable / Food	\$17.37 – 28.20†
Home Heating Oil (HHO)	\$18.6

† Increased cost is selected randomly from a uniform distribution.

5.4.3.2 Downstream Impacts of Cargo Impedance on Consumers

In addition to the immediate expenses faced by vessel owners, operators, or transportation firms, the delay in cargo shipments has an impact on the downstream consumers of the goods being transported. The actual impact could vary among individual consumers based on the specific good delayed, the length of the delay, and the supply chain resiliency, however, this extent of detailed information was unavailable from existing data sources. Based on current studies[11] of the economic impact of cargo delays, a range of costs to downstream consumers was selected for each type of cargo. The costs range from \$0 to \$20 per hour per \$10,000 of impeded cargo value, depending on the time sensitivity of the cargo (e.g., in D1, dry bulk ranks on the low end and HHO on the high end). In District 9, the level of the impact is also driven by the sub-season.

5.4.3.3 Flooding Impacts

Consequences of flooding events are based primarily on the estimated impacts of analogous historical incidents[12]. Based on historical data available from the NOAA National Climatic Data Center (NCDC), the probability of ice-induced flooding occurring in waterways along the coast of Maine in the absence of available ice breaking assets was determined for each week in the ice season. The impact of flooding was

[9] In an acute period of shortage, the heating oil distribution network may not have the capacity to deliver all required heating oil without incurring additional operating costs or experiencing degradation in service to other areas.
[10] Vessel operating costs were provided by the Lake Carriers' Association. Due to the business sensitivity of the data, the breakdown of these costs is not provided here.
[11] Martonosi, Susan E., David S. Ortiz, and Henry H. Willis. Evaluating the Viability of 100 Per Cent Container Inspection at America's Ports. Santa Monica, CA: RAND Corporation, 2005. http://www.rand.org/pubs/reprints/RP1220.
[12] USACE (2002). Engineering and Design: Ice Engineering. Manual 1110-2-1612. Washington, DC, U.S. Army Corps of Engineers.

similarly simulated based on the historical impact of flooding in each of the waterways identified as flood-prone. For example, historic consequences on the Kennebec River in Maine have ranged from $0 to $1.3M.

5.5 DOMICE Model Outcomes

The primary DOMICE simulation outcomes include the total economic impact of waterway closures for each District over the entire winter navigation season.

Additional simulation outcome calculations assess the effect of the modeling approximation that assets are assigned to a single waterway or waterway system for an entire week. This effect is assessed by calculating the number of unused hours of assigned icebreakers, or the number of hours that assigned icebreakers would have available in a week beyond what is needed to keep their assigned waterways clear.

The outcomes of the model report the results of the assessment for a user-specified number of Monte Carlo iterations[13]. Each Monte Carlo iteration of the model uses a single year's weather data and randomly selects across all the other uncertain inputs, such as asset availability, to determine the risk for that set of inputs. By simulating multiple combinations of variable inputs, the model produces a probabilistically representative sample of potential outcomes. In line with the objective of the DOMICE Simulation Model to address factors of uncertainty, this model output allows decision makers to understand both the range of possible outcomes and the relative likelihood of these outcomes.

The following series of figures show the total risk (economic impact), and breakdown by District for the current deployment and potential SLEP-driven reductions in available 140' WTGBs, as shown in Table 13. "Current Deployment" represents the force allocation of the last few winters with a 140' WTGB deployed from D1 to D9. "Alternative 1" reduces resources by one 140' WTGB in D9. "Alternative 2" additionally reduces resources by one 140' WTGB in D1, but back-fills it with a 225' WLB.

Table 13. Ice breaking resource deployment.

Asset Class	Current Deployment	Alternative 1	Alternative 2
District 1			
140 WTGB	3	3	2
65' WYTL	8	8	8
225' WLB	2	2	3
175' WLM	4	4	4
District 9			
240' WLBB	1	1	1
140' WTGB	6	5	5
225' WLB	2	2	2
1050 or 1100 (Canadian)	2	2	2

Assuming a probabilistic distribution of historical ice conditions, the current deployment results in the risk profile shown in Figure 4.

[13] For a high-end 32-bit computer, the user would typically select a maximum of 20 to 25 iterations. On a 64-bit system, a user can select 40 to 50 iterations.

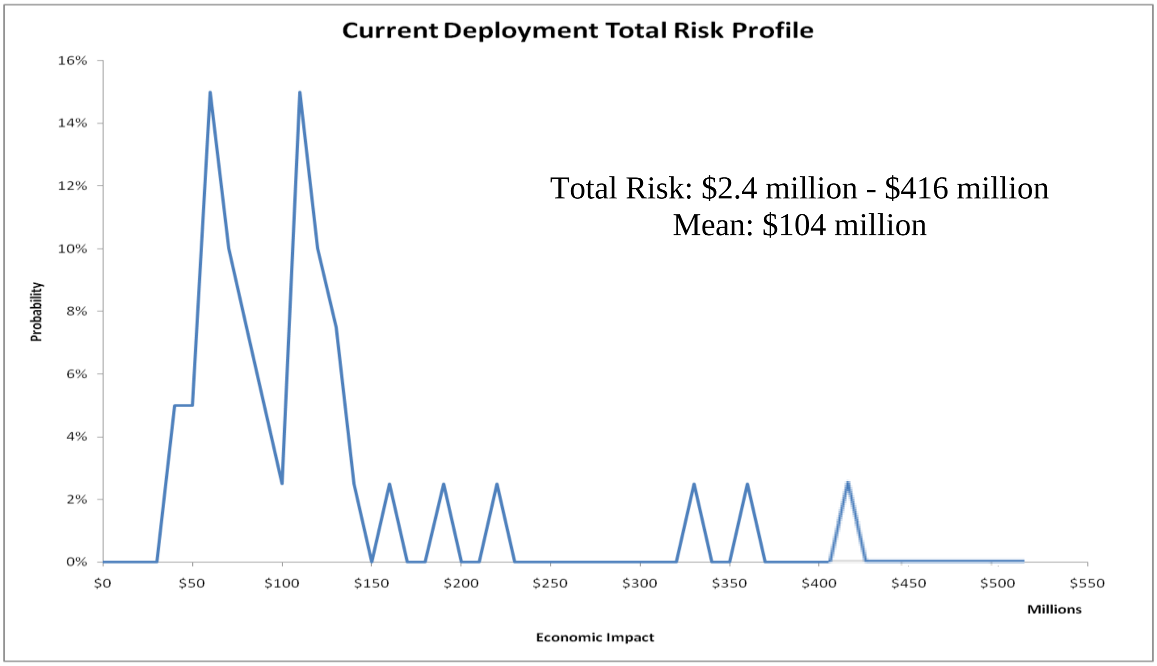

Figure 4. Current deployment total risk profile.

Figures 5 and 6 show the same risk distribution broken down for Districts 9 and 1. Note that the risk variability is much higher in D1, due to a greater variability in ice conditions.

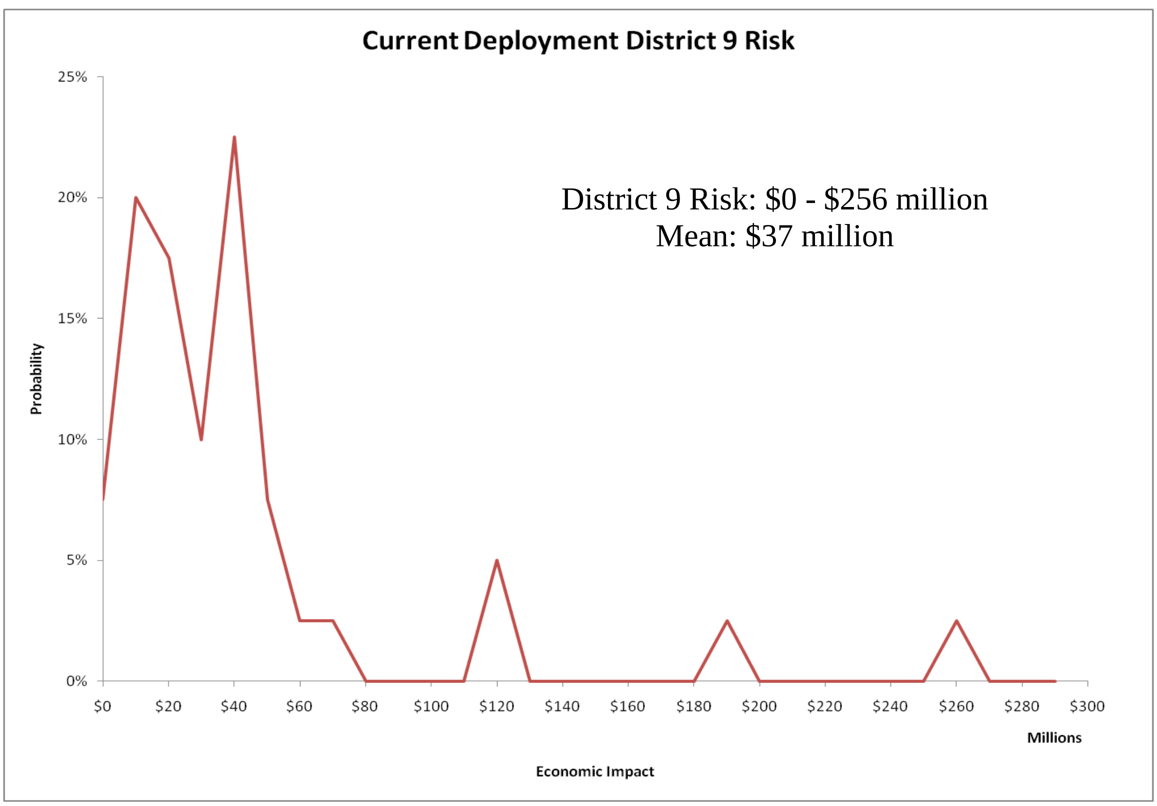

Figure 5. Current deployment District 9 risk.

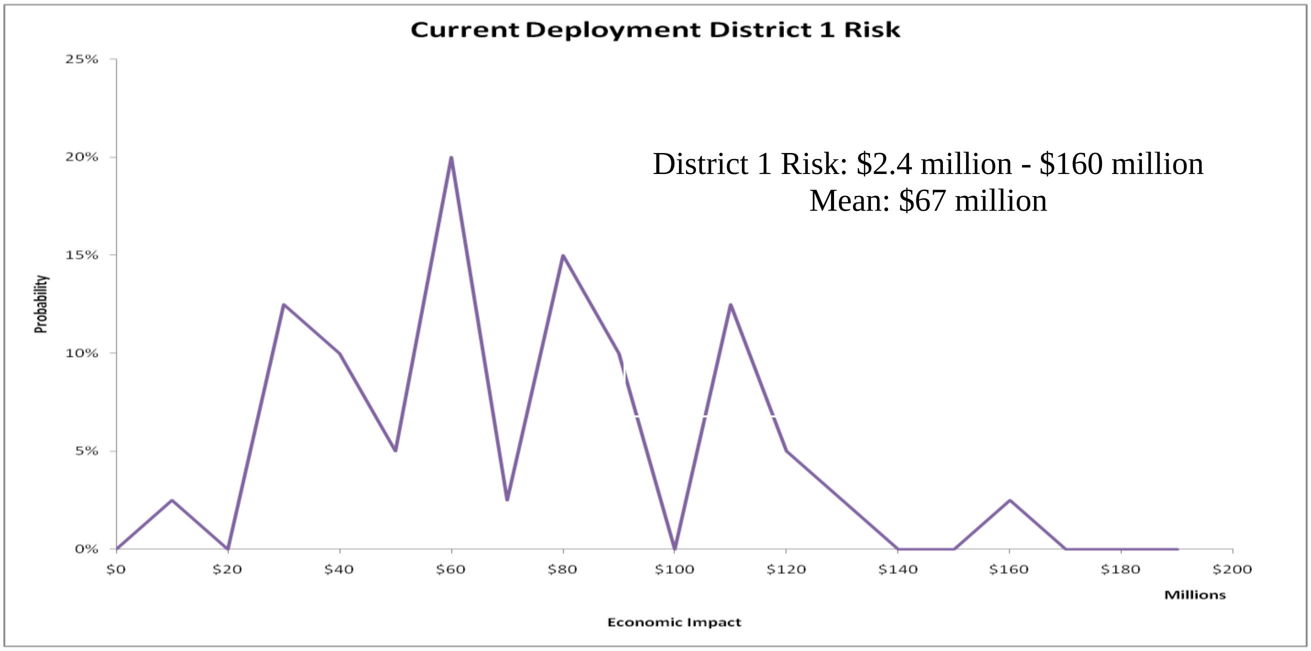

Figure 6. Current deployment District 9 risk.

Figures 7 and 8 show the change in risk due to a reduction in available 140' WTGBs, first by removing one from D9 (Alternative 1) and then by additionally removing one from D1 (Alternative 2) while adding a 225' WLB to D1. (Current risk is shown by a dotted line.)

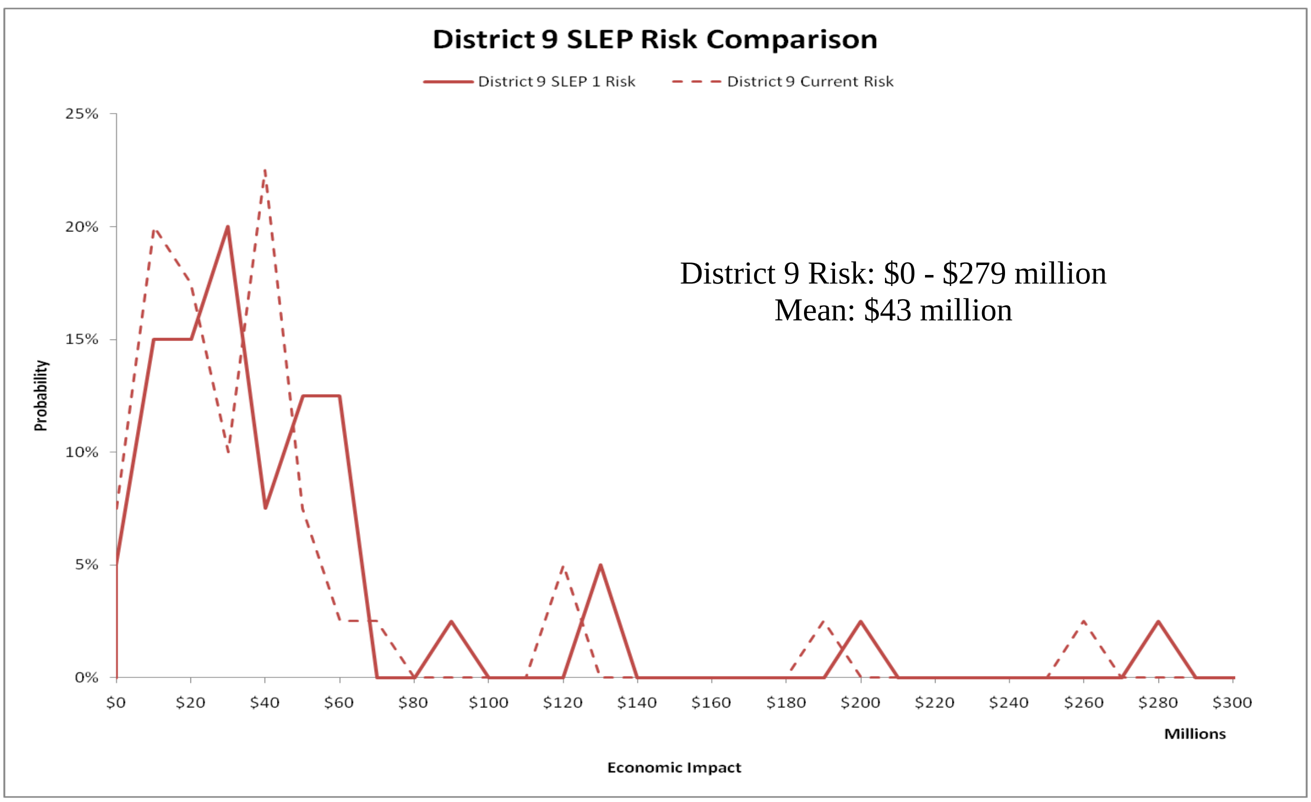

Figure 7. Alternative 1 District 9 risk comparison.

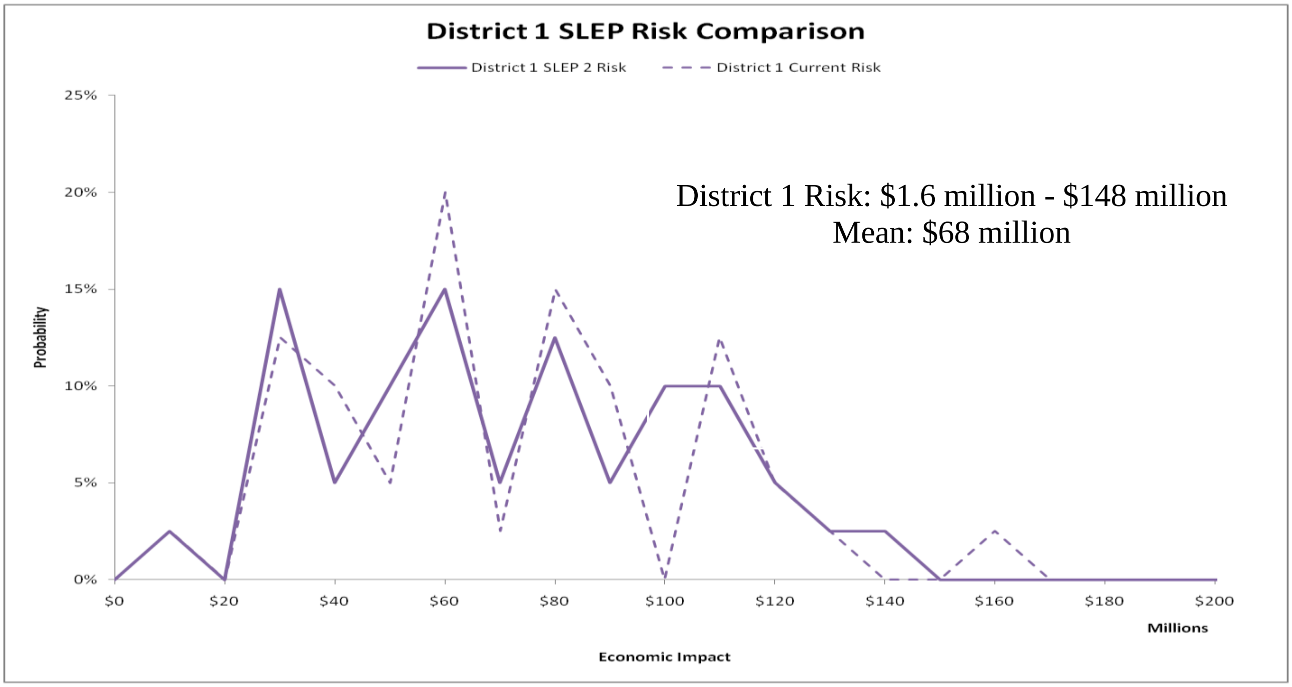

Figure 8. Alternative 2 District 1 risk comparison.

The model allows assessment of alternatives in terms of both average impacts and the range of possible impacts, given variability of factors such as weather and resource availability. As would be expected, the example assessments indicate that upcoming 140’ WTGB SLEP could have a large impact in a year with a severe winter, but that the risk to District 1 could be minimized by providing an additional 225’ WLB. Overall, if the winter were not severe, the impact of the 140’ WTGB SLEP would be moderate.

5.6 Potential Model Improvements

The DOMICE Simulation model represents a significant increase in the capability, reliability, rigor, and accuracy of the current DOMICE model. However, like all models, it remains an imperfect reflection of reality. In particular, limitations in data availability led to several modeling decisions that reduced the overall quantitative accuracy of the simulation model. While there are innumerable areas where this, like any model, could be improved, several key areas are highlighted here for future improvements.

District 1 Ice Conditions Prediction. Ice conditions for District 1 are generated based on a regression model that attempts to predict ice conditions based on air temperature. The regression model was created based on the relationships between air temperature and ice conditions that exist in District 9. The existing regression model has a low level of accuracy (low R2 scores), which contributes to model uncertainty surrounding the District 1 ice conditions. Additionally, using District 9 as a baseline assumes the relationship between weather and conditions is the same in District 1; due to differences in salinity, tides, and vessel traffic that may not be true. While this approach provides a reasonable approximation of ice conditions, it may misstate the absolute level of ice in District 1, and thus inaccurately predict the absolute level of risk. Ideally this process can be improved by following the approach in District 9 and directly collecting the ice thickness data in District 1. This would require working with the NOAA National Ice Center to begin gathering this data; this may be constrained by the available satellite information. Alternatively, gathering a small subset of ice direct ice data from District 1, along with other possible independent variables, could be used to build a more robust regression model.

Model Time Step. The model currently operates on a weekly time step. The model assigns vessels and measures economic impact on a weekly basis, though in reality a vessel could be assigned to multiple waterways in the same week. As most impeded waterways are cleared within one to three days, assigning an impact for an entire week likely overstates the absolute level of economic impact evaluated in the model. The weekly time step in the model is driven largely by the available information on icing condition in District 9, which are produced on a weekly basis. If reliable data was available on a consistent daily basis it could improve model granularity and fidelity.

Assignment of Multiple Types of Assets to a Single Waterway. The model's "dynamic" assignment sub-modules do not make assignments of more than one type of asset at a time for a particular type of clearing. For example, the assignment sub-modules might make an assignment of two 140s to a direct/active clearing in a particular waterway, but it would not assign both the 240 and a 140 to a direct/active clearing in the same waterway, unless those assignments are made as an "advance" or "static" assignment. This could result in over-estimation of impacts of ice in long waterways if in the real world, simultaneous assignments of more than two assets, or of assets of multiple types, would be made to clear ice in that waterway. If such an event occurs regularly occurs in a particular waterway in the model, then it could be straightforward to specify enough advance assignments (or "static assignments") to that waterway to keep it clear. Otherwise, the issue may not be easy to address within the current model structure, because of the number of combinations possible. One way would be to redesign the assignment process to use the Analytica Optimizer edition where asset assignment would presumably be framed as an integer programming optimization problem.

Economic Impact Modeling. The economic impact models are built around general expected impacts for types of cargo and the general type of impact to the wider economy. This is particularly pertinent in the case of impacts to downstream consumers of delayed goods. This general approach to downstream economic impacts treats all delays of a certain quantity of goods as economically equivalent, which is unlikely to mirror the reality of the supply chains in the specific Districts. While the relative levels of economic impacts are consistent, the absolute level of economic impact may be inaccurate. Additional modeling and research could develop more robust models of the supply chains for taconite, steel, and coal in District 9 and home heating oil in District 1.

6. Model Use and Applications

The DOMICE Simulation Model provides USCG Atlantic Area the ability to assess risk associated with ice breaking asset deployments and variations in operational and natural environments. The model's output of the total economic impact of waterway closures informs USCG decision-making processes involved in ice breaking asset allocations in Districts 1 and 9. The model's adaptability based on user-specified inputs allows the risk analysis to focus on specific risk-related scenarios. For example, the risk associated with the assignment of one 140-foot WTGB to a Service Life Extension Program can be analyzed by removing this asset from the icebreaker fleet in a run of the model. Additional manipulation of model inputs allows the user to observe changes in risk as a function of varying winter conditions that may reduce or increase the impacts of assigning the asset to SLEP. By allowing for these and other adjustments of the inputs of the model, the DOMICE Simulation Model strengthens ORAM's ability to represent the risk involved with a number of possible deployment and operating scenarios in order to ensure the most effective utilization of USCG assets in Districts 1 and 9.

The model is not 100% accurate; no model is. The inaccuracies in this model likely lead to an overstatement of the economic impact of waterway closures. This inaccuracy is primarily due to the one-week time step in the model, which is based on the weekly reporting of ice data, and which results in the cost of closures being calculated based on week-long intervals. Historically, delays have been addressed in a matter of days. While the model overstates the absolute impact of closures, it does so consistently so that the relative impact (risk) of various force laydowns may be compared to support decision making.